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# Compliance with the Verification of Environmental Technologies for Agricultural Production Protocol in Ammonia and Particulate Matter Monitoring in Livestock Farming: Development and Validation of the Adherence VERA Index

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**Abstract**

Air emissions from livestock farming, particularly ammonia ($NH_3$) and particulate matter ($PM_{2.5}$ and $PM_{10}$), constitute a major environmental and occupational health concern. The aim of this work was to assess the compliance with the Verification of Environmental Technologies for Agricultural Production (VERA) protocol in livestock emission monitoring studies and to propose the Adherence VERA Index (AVI) as a novel quantitative tool for standardizing methodological evaluation. A literature search was conducted in PubMed and Scopus, identifying 26 eligible studies published between January 2012 and June 2025. Data were extracted on farm characteristics, analytical methods, environmental variables, and emission outcomes, and evaluated across the five VERA protocol domains. The review revealed substantial methodological heterogeneity and overall suboptimal compliance with the VERA protocol, with frequent deficiencies in the reporting of key parameters such as ventilation rate, sampling strategy, and emission estimation methods. In this context, the AVI, by condensing core VERA requirements into a concise and operational metric, may facilitate protocol uptake and improve reporting compliance compared with the full VERA framework. Notably, several studies reported $NH_3$, $PM_{2.5}$ and $PM_{10}$ concentrations exceeding occupational and environmental exposure thresholds, particularly in swine and poultry farms, highlighting critical risks to workers' health. These findings underscore the need for enhanced standardization, integration of occupational health metrics, and improved air quality monitoring to ensure reliable exposure assessment and to safeguard both environmental and worker health in the livestock sector.

**Keywords:** ammonia; particulate matter; farms; VERA; health; AVI

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## 1. Introduction

Air pollution from intensive livestock farming is a major source of ammonia ($NH_3$) and particulate matter ($PM_{2.5}$ and $PM_{10}$). Livestock contributes approximately 81% of global $NH_3$ emissions [1], primarily through manure management, housing systems, and field practices [2]. In Europe, manure management alone accounts for 42% of livestock-related $NH_3$ emissions, with cattle representing the primary source [3]. Emission levels vary across countries and are influenced by factors such as climate, housing design, manure management practices, ventilation systems and animal husbandry conditions [4–6]. $NH_3$ is generated through the microbial degradation of urea and feces [7], contributing to environmental impacts including acidification and eutrophication [8].

PM emissions from livestock systems are predominantly generated indoors, particularly from feed and bedding materials [2], and arise from both direct dust release and secondary gas-to-particle conversion processes, in which $NH_3$ plays a key role [9]. Specifically, $NH_3$ reacts with atmospheric acids to form $PM_{2.5}$ [10,11], a pollutant associated with substantial adverse health effects. Occupational exposure to $NH_3$ and $PM_{2.5}$ can negatively affect farmers' respiratory health and has been linked to chronic diseases [11]. Globally, approximately 90% of the population is exposed to $PM_{2.5}$ concentrations exceeding WHO recommended limits [12].

Despite existing of regulatory frameworks [13–15], enforcement and emission standards vary widely across countries [16], and workplace concentrations frequently exceed legal thresholds. $NH_3$ and PM emissions also adversely affect animal health, particularly in confined systems such as poultry and pig housing, ultimately reducing productivity and compromising animal welfare [17,18].

Effective monitoring of these emissions is essential to mitigate their environmental and health impacts. Several monitoring protocols have been developed for this purpose [19–21]. Among these, the Verification of Environmental Technologies for Agricultural Production (VERA) test protocol provides standardized guidelines for evaluating emissions from specific livestock housing and management systems, defining requirements for testing conditions, sampling strategies, measurement techniques, and data interpretation tailored to different livestock categories [21]. The VERA protocol is a voluntary international framework established through cooperation among Denmark, Germany and the Netherlands, and coordinated under the VERA Secretariat. Although not mandatory, it is recognized by several European authorities and technical bodies as a harmonized assessment scheme for livestock-related emission mitigation technologies. In some countries, VERA results are used to support national approval processes or to inform environmental permitting, and the protocol has gained increasing attention as a consistent reference tool complementing existing guidance documents, including those related to Best Available Techniques (BAT) [4].

Growing scientific and regulatory attention has driven advances in emission monitoring technologies. However, the wide range of methodological approaches used to measure $NH_3$, $PM_{2.5}$, and $PM_{10}$ in livestock environments hampers data comparability and limits the robust evaluation of mitigation strategies [22–24]. This study therefore aimed to assess the methodological adherence of $NH_3$ and PM monitoring practices in livestock farming to the VERA protocol and to introduce a novel quantitative metric, the Adherence VERA Index (AVI), to objectively evaluate reporting quality and completeness across studies.

## 2. Materials and Methods

Papers were identified through searches of the PubMed and Scopus databases. Only original research articles published in English were considered, and the following search strings were used: (farm[Title/Abstract]) AND (particulate matter[Title/Abstract])) AND (monitoring[Title/Abstract]), ((farm[Title/Abstract]) AND (ammonia[Title/Abstract])) AND (monitoring[Title/Abstract]). Relevant keywords were identified through background reading, including different spellings, tenses and word variants, synonyms and related concepts. In addition, the reference lists of selected studies were manually screened to ensure comprehensive coverage of the relevant literature.

Screening of titles, abstracts and full texts was performed according to the Preferred Reporting Item for Systematic Review and Meta-analyses (PRISMA).

### 2.1. Inclusion/Exclusion Criteria

Studies conducted between January 2012 and June 2025 were included, if they were published in English and employed an observational study design, with a clear description of the applied methodology and reported measurements of $PM_{2.5}$, $PM_{10}$ and $NH_3$. Reviews, conference proceedings, editorials, articles with unavailable full text, studies lacking statistical data, or those published outside the predefined time period were excluded.

### 2.2. Data Extraction

Three authors (MP, PR, PRD) independently reviewed all retrieved articles and extracted the relevant data. Titles and abstracts were initially screened to identify potentially eligible studies, followed by full text assessment to confirm the eligibility. For each included study the following data were extracted: first author and year, study location, farm type, animal species, feed characteristics, flooring and manure management systems, farm size n and other site specific characteristics (e.g., ventilation, humidity and temperature), as well as analytical methods including instrumentation, filter types, mathematical models and data quality assessment. Extracted data were cross-checked among reviewers, and disagreements were resolved by discussion or, when necessary, by consultation with two additional authors (MF, CA).

### 2.3. Evaluation of Adherence to the VERA Protocol

Adherence to the VERA protocol for Livestock Housing and Management Systems in the selected studies was evaluated by two independent researchers (PR and MP) using the VERA Test Protocol Version 3:2018-09. Key parameters and procedures defined in the protocol were examined and organized into five tables (Tables S1–S5). A binary scoring system was applied to each parameter (1 = reported; 0 = not reported). The total score for each study was subsequently calculated to determine its overall alignment with the VERA protocol. All VERA domains were weighted equally, as the protocol does not prescribe differential weighting and is intended to ensure uniform methodological adherence.

The VERA test protocol was selected because, unlike broader frameworks such as IPCC or EMEP/EEA guidelines, it provides highly detailed, species-specific operational requirements tailored to livestock housing and management systems. Its structure includes precise guidance on sampling strategies, instrumentation, ventilation assessment, and emission estimation, making it particularly suitable for evaluating on-farm $NH_3$ and PM monitoring practices. This specificity to livestock environments represents a key advantage in promoting methodological comparability across studies.

### 2.4. Adherence VERA Index (AVI)

The short list of criteria was developed based on the 5 domains of the VERA protocol, from which the most frequently applied parameters and those considered indispensable by subject-matter experts in the field were selected (Table 1).

For each article included in the review, the adherence VERA index (AVI) was calculated by assigning a score of 1 to each reported criterion. The final AVI value was then computed using the following formula.

$$\text{AVI} = \text{number of reported criteria}/\text{number of applicable criteria} \times 100$$

**Table 1.** VERA-short minimum reporting set.

| | Category | Minimum Reporting Requirement |
|---|---|---|
| Description of the Housing system | Animal category | Species and breed |
| | Construction and dimensions | Materials, insulation, compartments, capacity, length, width and height |
| | Ventilation system and its design | Ventilation types, sizes and numbers of air inlets and outlets, capacity, set point values, air inlets/outlets |
| | Manure parameters | Amount [$m^3$] (M), |
| | Feeding | Strategy and frequency |
| Description of the measuring system (for ammonia and pm measurement) | Ammonia | Technical components: Material and characteristics, functional description and design |
| | Ammonia | Operational parameters: Ranges |
| | $PM_{10}$ | Technical components: Material and characteristics, functional description and design |
| | $PM_{10}$ | Operational parameters: Ranges |
| | $PM_{2.5}$ | Technical components: Material and characteristics, functional description and design |
| | $PM_{2.5}$ | Operational parameters: Ranges |
| Primary Parameter and Sampling conditions | Ammonia | Cumulative sampling up to 24 h or continuous measuring methods based on hourly values (24 samples) |
| | Ammonia | Sampling location: see measuring strategy (i.e., if naturally or mechanically ventilated) |
| | Ammonia | Calibration of the measuring instruments |
| | $PM_{10}$ | Cumulative sampling up to 24 h or continuous measuring methods based on hourly values (24 samples) |
| | $PM_{10}$ | Sampling location: see measuring strategy (i.e., if naturally or mechanically ventilated) |
| | $PM_{10}$ | Calibration of the measuring instruments |
| | $PM_{2.5}$ | Cumulative sampling up to 24 h or continuous measuring methods based on hourly values (24 samples) |
| | $PM_{2.5}$ | Sampling location: see measuring strategy (i.e., if naturally or mechanically ventilated) |
| | $PM_{2.5}$ | Calibration of the measuring instruments |

## 3. Results

A total of 534 articles were identified through the database search. Of these, 424 were excluded due to duplicate records or lack of relevance to the topic. The remaining 110 articles were screened based on titles and abstracts, resulting in the exclusion of 9 additional articles for irrelevance. The full texts of the remaining 101 articles were subsequently assessed for eligibility, and 72 studies were excluded for the following reasons: 8 due to inadequate sampling materials, 21 due to missing emission data, 43 because they were not conducted in livestock settings, and 3 because they were not published in English. Ultimately, 26 articles were included in this methodology review. The complete process of study identification, screening, and eligibility assessment is presented in Figure 1.

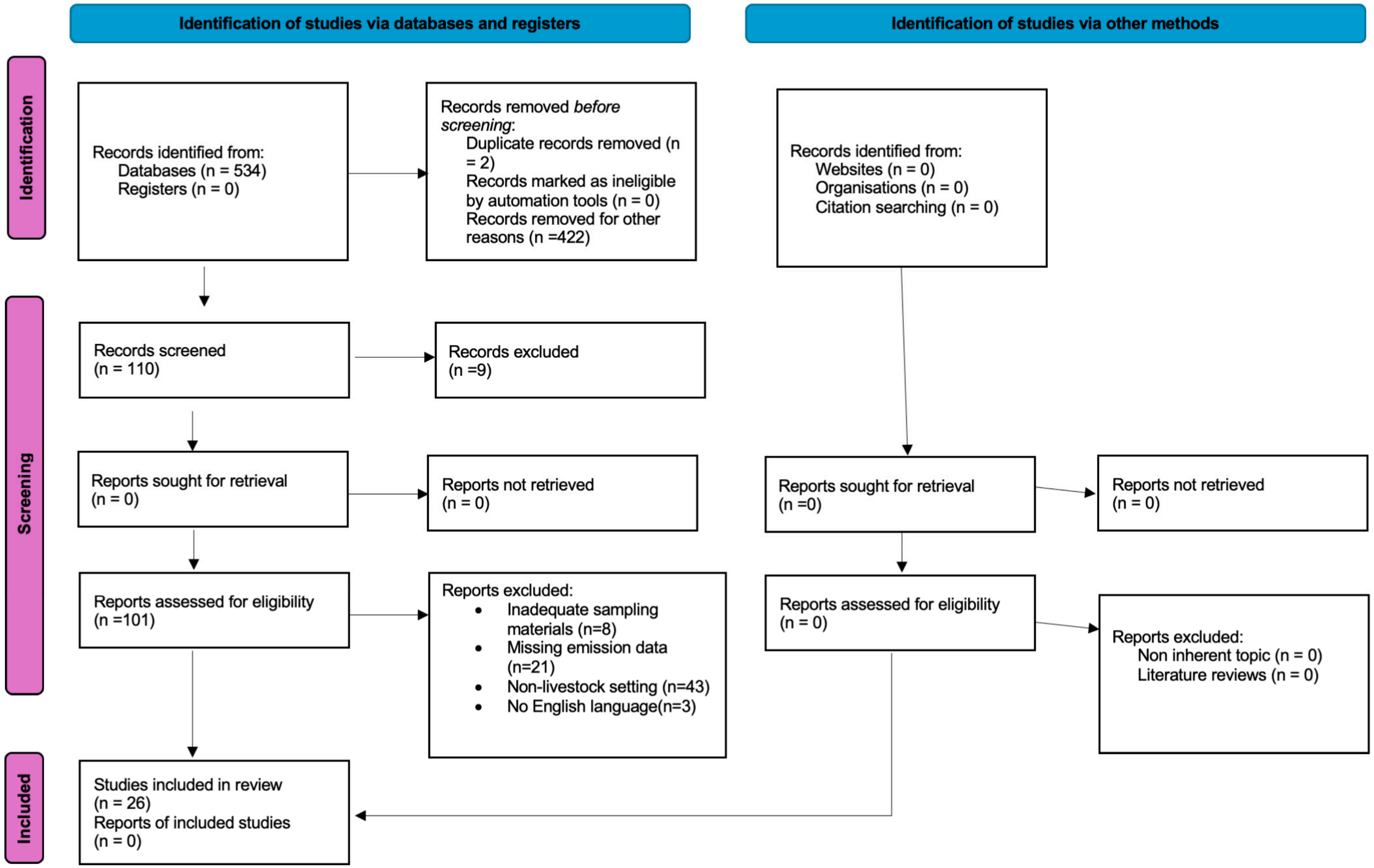


**Figure 1.** PRISMA 2020 Flow chart of the studies selection process.

### *3.1. General Characteristics of the Monitored Sites*

The general characteristics of livestock farming systems and monitoring data are reported in Table 2. The 26 included studies were conducted across several countries, including the United States (13 studies), China (8 studies), South Korea (2 studies), Germany (1 study), the Netherlands (1 study), and Poland (1 study). The monitored farms involved different livestock species, including swine, poultry (laying hens and broilers), and dairy cattle [25–29]. Reported animal numbers ranged from 10 individuals [30] to more than 400,000 hens [31], although this information was frequently not reported.

Housing characteristics varied considerably, with flooring systems including slatted, concrete, and open litter floors [32–34]. Manure management practices ranged from liquid manure pits and slanted boards to mechanical scrapers and manure belts [35–37]. Most facilities utilized mechanical or mixed ventilation systems, while some relied exclusively on natural ventilation [38,39]. Environmental parameters such as temperature and humidity were generally monitored using sensors; in a limited number studies, advanced monitoring instruments were employed (e.g., Testo 420 flow hood in Choi et al., 2023; portable gas analyzers in Li et al., 2024) [25,40]. Lighting conditions were frequently not reported (Table 2).

**Table 2.** General characteristics of the included studies.

| Authors, Year | Place | Farm Type | General Characteristics | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Animals: -Number -Type** | **Feed, Type and Amount** | **Floor and Manure Management** | **Size Dimension (m)** | **Other Site Characteristics (Lighting, Temperature and Humidity, Ventilation)** |
| **1. Choi et al.,** 2023 [25] | Jangseong City, South Korea | Commercial pig farm | -≈9000<br>-pig | NR | **-Floor:** Slotted floors<br>**-Manure management:** liquid manure pit recirculation system | 75 × 13 × 4.7 m | **-Lighting:** NR<br>**-Temperature and humidity**: HOBO probe<br>**-Ventilation**: mechanical ventilation systems, monitored by flow hood (Model Testo 420). |
| **2. Ji Qin Ni et al.,** 2012 [26] | West Lafayette, USA | Commercial egg production farm | -NR<br>-Hen | NR | **-Floor:** NR<br>**-Manure-management**: slanted boards behind the cages | Area: 10,629.5 m$^2$ | **-Lighting:** NR<br>**-Temperature and humidity**: RH/T sensors and thermocouples<br>**-Ventilation:** natural from the attic through three temperature-adjusted V-shaped baffled ceiling and mechanical from 55 exhausted fans |
| **3. Jihoon Park et al.**, 2019 [39] | Republic of Korea | Five commercial swine farms and five poultry farms | -NR<br>-Finishing pig, Broiler and Laying hen | NR | **Floor:** slatted floors<br>**Manure management**: manure storage and manure composting facilities. | 7139 m$^2$ | **-Lighting:** NR<br>-**Temperature and humidity:** Indoor air quality meter<br>-**Ventilation**: Natural and mechanical ventilation. |
| **4. Qian-Feng Li et al.,** 2013 [41] | North Carolina, United States | Commercial egg production farm | -NR<br>-Chickens and turkeys | NR | NR | NR | **-Lighting**: NR<br>-**Temperature and humidity:** simultaneously monitored as part of the National Air Emissions Monitoring Study.<br>-**Ventilation**: six mechanically ventilated houses and three naturally ventilated houses. |
| **5. Dan Shen et al.,** 2019 [33] | Zunyi city of Guizhou province, China | Swine barns | -352<br>-Nursery pigs<br>-152<br>-Fattening pigs | Nursery pigs pelleted feed manually; the total amount of feed was 0.5 kg daily each. Fattening pigs 4.5 kg of pelleted feed using an automatic feeder | **-Floor:** slatted floor.<br>**-Manure management:** manure down the floor and stored approximately 3 months | 26.0 m × 15.0 m | **-High-rise nursery barn** (HN)<br>**-Lighting:** NR<br>**-Temperature and humidity:** Heat preservation lamp<br>**-Ventilation:** mechanical ventilation system consisting of exhaust fans<br>**-High-rise fattening** (HF)<br>**-Lighting:** NR<br>**-Temperature and humidity:** No Heat preservation lamp<br>**-Ventilation**: natural and mechanical |

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**Table 2.** *Cont.*

| Authors, Year | Place | Farm Type | General Characteristics | | | | |
|---|---|---|---|---|---|---|---|
| | | | Animals: -Number -Type | Feed, Type and Amount | Floor and Manure Management | Size Dimension (m) | Other Site Characteristics (Lighting, Temperature and Humidity, Ventilation) |
| **6. Y. Zhao et al.,** 2015 [37] | Midwest, United States | Poultry house | -200,000 -Laying-hen | NR | -**Floor:** Slatted floor -**Manure management:** manure belts in all hen colonies and conveyed the accumulated manure out of the house | NR | -**Lighting**: NR -**Temperature and humidity**: type-T thermocouples and RH with capacitance-type humidity sensors -**Ventilation:** mechanical ventilation |
| **7. Yu Wang et al.,** 2020 [38] | Yanqing District of suburb Beijing, China. | Poultry house | -100,000 -Laying hen | Feed by rows of troughs, and water via nipple drinkers. | **Floor:** 2 slatted floors. **Manure management:** collected on wide plastic belts beneath each tier of cages. | 115 × 14 × 7.5 m | -**Lighting:** The Lighting period lasted from 4:00 to 20:00 daily. -**Temperature and humidity:** temperature-controlled sensors **Ventilation**: negative pressure ventilation system |
| **8. Yaomin Jin et al.,** 2012 [42] | State of Indiana, in the United States Missouri, Columbia | Swine finishing farm | -8000 -Pigs | NR | -**Floor**: fully slatted -**Manure management:** stored in a deep pit under the floor for about 6 months before removal. | 2 Farms: 126 × 25.5 m | -**Lighting**: NR -**Temperature and humidity**: NR -**Ventilation:** each room mechanically and naturally ventilated |
| **9. Li Q.-F. et al.,** 2013 [43] | North Carolina. Monitoring was recorded from 24 Sept 2007 to 27 October 2009 | Eggs production facility | -103,000 -Hy-Line W36 hens | NR | **Floor:** NR **Manure management:** skid loader | 177 × 18 m | **Lighting:** NR **Temperature and humidity**: temperature sensors **Ventilation**: mechanical and naturally ventilation |
| **10. Casey et al.,** 2012 [44] | Site OK4B was in the Panhandle region of Oklahoma (USA). | Sow stalls | -1200 -sows in six rows of sow stalls | Feed truck deliveries. | -**Floor:** slatted and concrete -**Manure management**: shallow pit allowing to drain in an anaerobic lagoon | 16 rooms: 129 × 18 m | **Lighting:** NR **Temperature and humidity:** temperature sensors **Ventilation:** mechanical |
| **11. Li et al.,** 2018 [45] | Zunyi city of Guizhou province, monitored from April1st to April 20th, 2017. | Swine farm: nursery and fattening stables | -Five commercial swine farms and five poultry farms were selected for monitoring. | Fed manually. | -**Floor:** slatted -**Manure management:** underneath the slatted floor and stored for about three months | 26 × 15 m | -**Nursery Farm** **Lighting:** Insulation lamp -**Temperature and humidity:** Sensors -**Ventilation:** No ventilation in nursery -**Fattening Stable** **Lighting:** Not insultation lamp -**Temperature and humidity:** Sensors -**Ventilation:** Mechanically |
| **12. Hayes et al.,** 2012 [32] | Iowa states from June 2010 to December 2011. | Two Aviary houses | -50,000 -hens (Hy-Line Brown) | Feed manually | -**Floor:** open litter -**Manure management:** 3 levels with manure belts and manure drying air duct | 167.6 m × 19.8 m | -**Lighting**: Fluorescent lamp used for 16 h light period -**Temperature and humidity:** Sensors -**Ventilation:** Mechanically |
| **13. Von Jasmund et al.,** 2020 [30] | University Bonn from March to July 2019 | Fattening stable | -11 -weaned and docked pigs | Feed a libitum on a wet feeder, including two nipple drinkers | **Floor:** Partly slatted concrete **Manure management**: NR | 6.00 × 2.54 m | -**Lighting:** NR -**Temperature and humidity:** Tinytag sensor -**Ventilation:** Mechanically |
| **14. Wu et al.,** 2020 [46] | Beijing, China in May 2017 | Dairy farm | -300 -cows | Feed manually | -**Floor**: Brick and a cowshed with a solid concrete floor. -**Manure management**: scrape every day and store in a vacant cowshed | NR | -**Lighting:** NR -**Temperature and humidity**: thermo-anemometer -**Ventilation:** mechanically |

**Table 2.** *Cont.*

| Authors, Year | Place | Farm Type | General Characteristics | | | | |
|---|---|---|---|---|---|---|---|
| | | | Animals: -Number -Type | Feed, Type and Amount | Floor and Manure Management | Size Dimension (m) | Other Site Characteristics (Lighting, Temperature and Humidity, Ventilation) |
| **15. Joo et al.**, 2015 [27] | Washington State, located in the United States Pacific Northwest | Dairy barns with curtains | -1250<br>-Dairy cows:<br>B1: 400 cows<br>B2: 850 cows | NR | NR | B1:<br>183 × 31 m<br>B2:<br>213 × 39 m | **-Lighting:** NR<br>**-Temperature and humidity:** RH/T sensor<br>**-Ventilation**: mechanically |
| **16. Jin et al.**, 2010 [47] | Indiana, USA | Dairy farm | -3400<br>-Dairy cows | Feed and water provided at libitum | **-Floor:** a raised platform with beds and a lower walkway made of iron slat.<br>**-Manure management:** with scrapers and sent to a reception pit | 472 m × 29 m | **-Lighting:** NR<br>**-Temperature and relative humidity:** RH/T sensor<br>**-Ventilation**: mechanically |
| **17. Garcia et al.**, 2013 [48] | California located in the Central Valley | 13 large dairies | -130,000<br>-Lactating cows | NR | NR | Area: 120–1320 $m^2$<br>Median Area: 610 $m^2$ | **-Lighting**: NR<br>**-Temperature and humidity:** California Air Resources Board<br>**-Ventilation:** mechanically |
| **18. Dai et al.**, 2018 [35] | South China (113° 04.888′ E, 28° 11.247′ N), | Hog houses | -600<br>-piglets | NR | **-Floor:** ground slatted floor with<br>**-Manure management:** 4 methods: manual waterless, automatic waterless, automatic water flushing and fermentation bed. | 20 × 10 × 3.5 m | **-Lighting**: natural light<br>**-Temperature and humidity**: T sensors<br>**-Ventilation:** Naturally and mechanically ventilated |
| **19. Shepherd et al.**, 2015 [36] | US Midwest | 3 house egg production systems with a 200,000-hen capacity; | -NR<br>-Lohmann white hens | Feed twice per day in each house Drinking ad libitum | **-Floor**: NR<br>**-Manure management:** belts | CC: 141.2 × 26 m<br>AV: 152.2 m × 21.3 m<br>EC: 154.2 × 13.7 m | **-Lighting**: 12 h light and 12 h dark<br>**-Temperature and humidity**: RH/T sensors<br>**-Ventilation**: mechanically |
| **20. Tamar Tulp et al.**, 2024 [29] | Friesland, Netherlands | Dutch commercial dairy | -250<br>-cows | Feed manually | **-Floor**: NR<br>**-Manure management:** NR | About 27,000 $m^2$ | **-Lighting**: NR<br>**-Temperature and humidity:** RH/T sensor<br>**-Ventilation:** Mechanically |
| **21. Schmithauesen et al.**, 2018 [34] | Kleve, Germany | Dairy barn | -96<br>-lactating cows | Feed manually | **-Floor**: Slatted floors **-Manure management:** an under-floor concrete slurry storage system | 68 × 34 m. Height from 5.15 to 12.35 m. | **-Lighting**: NR<br>**-Temperature and humidity**: an outside weather station at a height of 6 m on the rooftop<br>**-Ventilation:** Mechanically and naturally |
| **22. Zenon Nieckarz et al.**, 2023 [49] | Kraków, Poland | Commercial dairy cattle | -84<br>-dairy cows | TMR Feed | **-Floor**: NR<br>**-Manure management:** NR | 10.39 × 54.87 m height from 3.82 m to 5.37 m | **-Lighting**: NR<br>**-Temperature and humidity:** RH/T sensors<br>**-Ventilation:** Mechanically |
| **23. W. Zheng et al.**, 2020 [31] | Midwest, United States | Commercial laying hen house | -425,000<br>-laying hens | NR | **-Floor:** halfway between the ground and ceiling, forming the top and bottom floors.<br>**-Manure management:** a belt under each cage | 27.8 × 164.6 × 10 m | **-Lighting**: NR<br>**-Temperature and humidity**: RH/T sensors<br>**-Ventilation:** Mechanically |
| **24. Zhifang Shi et al.**, 2019 [28] | Henan, China | Dairy farms | -1450<br>-Holstein cows. | Feed manually with a mixed ration (TMR) | NR | Farm1: 72 × 31 × 7<br>Farm2: 72 × 26 × 6<br>Farm3: 96 × 27 × 7 | **-Lighting**: NR<br>**-Temperature and humidity**: RH/T sensors<br>**-Ventilation**: Naturally |

**Table 2.** *Cont.*

| Authors, Year | Place | Farm Type | General Characteristics | | | | |
|---|---|---|---|---|---|---|---|
| | | | Animals: -Number -Type | Feed, Type and Amount | Floor and Manure Management | Size Dimension (m) | Other Site Characteristics (Lighting, Temperature and Humidity, Ventilation) |
| **25. Jannat A et al.,** 2025 [50] | Northen Colorado, USA | Dairy farms | -6000 -lactating cows | Feed manually every night | **-Floor:** NR **-Manure management:** vacuum machine pulled by a tractor | NR | **-Lighting:** NR **-Temperature and humidity:** RH/T 2.5% logger sensors **-Ventilation:** forced ventilation and misting systems, |
| **26. Li et al.,** 2024 [40] | Hebei Province, Northen China | Low profile, cross ventilated dairy barn | -2400 -lactating cows | 4 Feed delivery alleys | **-Floor:** NR **-Manure management**: manure removal alleys renewed by a mechanical truck | 408 × 92 m | **-Lighting:** artificially with LED **-Temperature and humidity:** portable particulate monitoring unit (PPMU) and a portable gas monitoring unit (PGMU) **Ventilation:** two positive-pressure ventilation pipes |

## *3.2. $NH_3$ and PM Monitoring Data by Animal Species*

### 3.2.1. Swine Farms

Ammonia ($NH_3$) emissions and concentrations in swine farms exhibited substantial variability across studies. In a South Korean pig farm, Choi et al. (2023) reported $NH_3$ emission rates of 0.31 ± 0.21 kg/animal/year for piglets and 1.85 ± 1.26 kg/animal/year for growing pigs [25]. Similarly, Von Jasmund et al. (2020) observed mean indoor $NH_3$ concentrations of 12.05 ± 6.94 ppm [30]. In China, Li et al. (2018) recorded $NH_3$ concentrations of 12.18 ± 3.36 mg/m$^3$ in nursery barns and 26.70 ± 6.78 mg/m$^3$ in fattening barns [45].

Particulate matter (PM) emissions also showed marked variability. $PM_{10}$ concentrations ranged from 0.338 ± 0.1 mg/m$^3$ in fattening barns [33] to substantially higher levels in other studies. $PM_{2.5}$ concentrations were generally lower; for example, Shen et al. reported mean values of 0.210 ± 0.09 mg/m$^3$ in nursery barns and 0.144 ± 0.06 mg/m$^3$ in fattening barns. Dai et al. (2018) examined different manure management strategies and reported $NH_3$ emission rates ranging from 48.01 ± 0.05 to 416.75 ± 0.28 µg/s, while $PM_{10}$ and $PM_{2.5}$ emission rates remained relatively low across housing types (Table 3) [35].

**Table 3.** Monitoring data of the included studies.

| Authors, Year | Monitoring Data |
|---|---|
| **1. Choi et al.,** 2023 [25] | **-$NH_3$ emission piglets ± SD:** 0.31 ± 0.21 kg/animal years; **$PM_{10}$ emission piglets ± SD:** 0.03 ± 0.03 kg/animal years; **$PM_{2.5}$ emission piglets ± SD:** 0.01 ± 0.01 kg/animal years; **$NH_3$ emission growing pigs ± SD**: 1.85 ± 1.26 kg/animal years; **$PM_{10}$ emission growing pigs ± SD:** 0.16 ± 0.17 kg/animal years; **$PM_{2.5}$ emission growing pigs ± SD**: 0.09 ± 0.10 kg/animal years |
| **2. Ji Qin Ni et al.,** 2012 [26] | **-$NH_3$ emissions barns HA:** 0.5–175.7 ppm 1st yr mean: 49.9 ± 39.6 ppm; 2st yr mean: 47.7 ± 38.3 ppm;<br>**HB:** 1.2–182.0 ppm—1st yr mean: 55.5 ± 44.2 ppm; 2st yr mean: 48.0 ± 36.2 ppm<br>**BA:** 1.1–61.3 ppm—1st yr mean: 14.6 ± 10.2 ppm; 2st yr mean: 12.0 ± 7.8 ppm;<br>**BB**: 0.2–57.2 ppm—1st yr mean: 12.0 ± 10.2 ppm; 2st yr mean: 13.8 ± 10.6 ppm<br>**-$PM_{10}$ emission barns:**<br>**HA:** 1–1719 ug/m$^3$—1st yr mean: 473 ± 285 ug/m$^3$; 2st yr mean: 616 ± 305 ug/m$^3$;<br>**HB:** 3–3270 ug/m$^3$—1st yr mean: 443 ± 203 ug/m$^3$; 2st yr mean: 668 ± 408 ug/m$^3$<br>**BA**: 0–2702 ug/m$^3$—1st yr mean: 438 ± 393 ug/m$^3$; 2st yr mean: 402 ± 447 ug/m$^3$;<br>**BB**: 0–4039 ug/m$^3$—1st yr mean: 929 ± 778 ug/m$^3$; 2st yr mean: 629 ± 516 ug/m$^3$ |
| **3. Jihoon Park et al.**, 2019 [39] | **$NH_3$ concentration:** laying hens (GM range: 6.9 and 57.9 ppm); swine farms (GM range: 5.9 and 43.2 ppm); broiler hen farms (GM range: 2.6 and 8.6 ppm) |
| **4. Qian-Feng Li et al.,** 2013 [41] | **PM Type**; **N** (number of hourly means); **Mean**; **SD Median**<br>$PM_{2.5}$; 1035; 12.3 ± 9.1; 10.0<br>$PM_{10}$ 14,369; 35.0 ± 40.7; 28.2 |

**Table 3.** *Cont.*

| Authors, Year | Monitoring Data |
| --- | --- |
| **5. Dan Shen et al.,** 2019 [33] | **$PM_{10}$ Mean ± SD**: high-rise nursery burns = 0.388 ± 0.09; high-rise fattening burns = 0.338 ± 0.1; Outside = 0.111 ± 0.07; **$PM_{2.5}$ Mean ± SD**: high-rise nursery burns = 0.210 ± 0.09; high-rise fattening burns = 0.144 ± 0.06; Outside = 0.0880 ± 0.05; **$NH_3$ Mean ± SD**: high-rise nursery burns = 12.2 ± 3; high-rise fattening burns = 26.7 ± 7; Outside = 2.27 ± 1 |
| **6. Y. Zhao et Al.,** 2015 [37] | **-$NH_3$ Mean ± SD mg/m$^3$**: Ambient: 0.4 ± 0.5; CC 4.0 ± 2.4; AV 6.7 ± 5.9; EC 2.8 ± 1.7<br>**$PM_{10}$, Mean ± SD mg/m$^3$**: CC 0.59 ± 0.16; AV 3.95 ± 2.83; EC 0.44 ± 0.18<br>**-$PM_{2.5}$, Mean ± SD mg/m$^3$**: CC 0.035 ± 0.013; AV 0.410 ± 0.251; EC 0.056 ± 0.021 |
| **7. Yu Wang et al.**, 2020 [38] | **-$NH_3$ concentration**: Mean ± SD mg/m$^3$: Summer: 3.9 ± 1.2; Autumn: 3.7 ± 1.6; Winter: 5.0 ± 1.1<br>**-$PM_{2.5}$ concentration:** Mean ± SD (mg/m$^3$): Summer: 100 ± 21; Autumn: 1.07 ± 2.5; Winter: 1.44 ± 6.8<br>**-$PM_{10}$ concentration:** Mean ± SD (mg/m$^3$) (mg/m$^3$): Summer: 35.4 ± 4.4; Autumn: 56.2 ± 4.8; Winter: 82.8 ± 9.7 |
| **8. Yaomin Jin et al.,** 2012. [42] | **NH3 concentration (SD):** 0.40 (0.09) |
| **9. Li Q.-F. et al.,** 2013 [43] | **$PM_{2.5}$ concentration:** Mean ± SD: 0.37 ± 3.06 mg d$^{-1}$ hen $^{-1}$<br>**$PM_{10}$ concentration:** Mean ± SD: 17.8 ± 14.9 mg d$^{-1}$ hen $^{-1}$ |
| **10. Casey et al.,** 2012 [44] | **$NH_3$ concentration:** Mean ± SD—B1: 9.25 ± 1.85 g d$^{-1}$ hen $^{-1}$; B2: 9.61 ± 1.28 d$^{-1}$ hen $^{-1}$; F9: 19.1 ± 6.0 d$^{-1}$ hen $^{-1}$ |
| **11. Li et al.,** 2018 [45] | **-Nursery Results concentration:** Mean ± SD $PM_{10}$: 0.39 ± 0.09 mg/m$^3$, $PM_{2.5}$: 0.21 ± 0.09 mg/m$^3$, $NH_3$: 12.18 ± 3.36 mg/m$^3$<br>**-Fattening Stable concentration**: Mean ± SD $PM_{10}$: 0.34 ± 0.10 mg/m$^3$, $PM_{2.5}$: 0.14 ± 0.06 mg/m$^3$, $NH_3$: 26.70 ± 6.78 mg/m$^3$ |
| **12. Hayes et al.,** 2012 [32] | **-Daily indoor aerial concentration:** Mean ± SD $NH_3$: 8.7 ± 8.4 ppm, $PM_{10}$: 2.3 ± 1.6 mg m$^{-3}$, $PM_{2.5}$: 0.2 ± 0.3 mg m$^{-3}$<br>**-Daily emission rates**: Mean ± SD (mg/m$^3$)—$NH_3$: 0.15 ± 0.08 g bird $^{-1}$, $PM_{10}$: 0.11 ± 0.04 g bird $^{-1}$, $PM_{2.5}$: 0.008 ± 0.006 g bird$^{-1}$ |
| **13. Von Jasmund et al.,** 2020 [30] | **$NH_3$ concentration:** Mean ± SD—$NH_3$: 12.05 ± 6.94 ppm |
| **14. Wu et al.,** 2020 [46] | **$NH_3$ concentration:** Mean-$NH_3$: 61.6 g a$^{-1}$ m$^{-2}$, $NH_3$: 8.63 kg a$^{-1}$ AP$^{-1}$, $NH_3$: 7.19 kg a$^{-1}$ AU$^{-1}$ |
| **15. Joo et al.,** 2015 [27] | **$PM_{2.5}$ Mass concentration (ug/m$^3$)** B1: 72.6 ± 8.1; B2: 67.8 ± 12.1; Ambient: 30.7 ± 9.4;<br>**$PM_{2.5}$ Emission rate (mg/min)** B1: 2.8 ± 1.4 B2: 2.5 ± 1.3<br>**$PM_{10}$ Mass concentration (ug/m$^3$)** B1: 330 ± 162; B2: 577 ± 280; Ambient: 247 ± 132;<br>**$PM_{10}$ Emission rate (mg/min)** B1: 10.7 ± 6.3; B2: 17.0 ± 10.0 |
| **16. Jin et al.,** 2010 [47] | **$NH_3$ emission rate (ppm):** From 18.53 to 20.13 ppm |
| **17. Garcia et al.,** 2013 [48] | **$PM_{2.5}$ emission rate Mean (range) [ug/m$^3$]** Geometric mean: 24 (2–116) ug/m$^3$; Arithmetic mean: 30 (2–116) ug/m$^3$ |
| **18. Dai et al.,** 2018 [35] | **-$NH_3$ emission rate (ug/s): H1:** from 93.85 ± 0.13 to 416.75 ± 0.28; **H2:** from 48.01 ± 0.05 to 241.12 ± 0.11<br>**-$PM_{10}$ emission rate (ug/h): H1:** 5.091 ± 0.285; **H2:** 5.187 ± 0.135; **H3:** 5.235 ± 0.559; **H4:** 5.379 ± 0.092<br>**-$PM_{2.5}$ emission rate (ug/h): H1:** 0.096 ± 0.048; **H2:** 0.096 ± 0.048; **H3:** 0.096 ± 0.048; **H4:** 0.048 ± 0.048<br>**-$PM_{10}$ concentration (min–max; average) [ug/m$^3$]: H1:** 6–756; 91; **H2:** 3–2140; 82; **H3:** 2–674; 80; **H4:** 3–1160; 76<br>**-$PM_{2.5}$ concentration (min–max; average) [ug/m$^3$]: H1:** 6–355; 56; **H2:** 3–728; 47; **H3:** 2–270; 43; **H4:** 3–561; 42 |
| **19. Shepherd et al.,** 2015 [36] | **-$NH_3$ emission rate (g/hen/d): CC:** from 0.068 ± 0.004 to 0.097 ± 0.01; **AV:** from 0.088 ± 0.006 to 0.136 ± 0.011; **EC:** from 0.049 ± 0.004 to 0.059 ± 0.006<br>**-$PM_{10}$ emission rate (mg/hen/d): CC:** from 14.5 ± 0.90 to 16.9 ± 1.02; **AV:** from 87.6 ± 3.92 to 113.0 ± 5.07; **EC:** from 13.9 ± 0.66 to 17.3 ± 0.90<br>**-$NH_{2.5}$ emission rate (mg/hen/d): CC:** from 0.9 ± 0.14 to 1.0 ± 0.24; **AV:** from 8.6 ± 0.32 to 9.1 ± 0.27; **EC:** from 1.5 ± 0.10 to 1.9 ± 0.15 |

https://doi.org/10.3390/environments13010024

**Table 3.** *Cont.*

| Authors, Year | Monitoring Data |
|---|---|
| **20. Tamar Tulp et al.,** 2024 [29] | **$NH_3$ concentration: NE direction:** 21–100 ug/m$^3$; **NW direction:** 6.6–56.7 ug/m$^3$; **SE direction:** 31.5–108.7 ug/m$^3$; **SW direction:** 7.5–36.7 ug/m$^3$ |
| **21. Schmith-auesen et al.,** 2018 [34] | **$NH_3$ emission (g/LU/d):**<br>Control group: P1: 18.4 ± 4.1; P2: 24.2 ± 9.6; P3: 30.0 ± 4.9; P4: 27.4 ± 2.0<br>Experimental group: P1: 19.8 ± 2.3; P2: 23.0 ± 6.0; P3: 22.3 ± 2.5; P4: 22.2 ± 3.5 |
| **22. Zenon Nieckarz et al.,** 2023 [49] | **-$PM_{10}$ concentration (ug/m$^3$)** Average daily outside: 150; Average daily inside: 138.8<br>**-$PM_{2.5}$ concentration (ug/m$^3$)** Average daily outside: 106; Average daily inside: 119 |
| **23. W. Zheng et Al.,** 2020 [31] | **$NH_3$ concentration (mean ± SD) [ppm]** A: from 0.0 ± 0.0 to 7.8 ± 2.8;<br>B: from 2.0 ± 2.6 to 22.0 ± 3.2; C: from 0.8 ± 1.9 to 20.4 ± 4.5; D: from 1.2 ± 2.2 to 28.1 ± 4.7 |
| **24. Zhifang Shi et al.,** 2019 [28] | **$NH_3$ concentration barns:** Mean 1.54 mg/m$^3$; Lactating barns 2.13 mg/m$^3$; Bon-lactating barns 0.83 mg/m$^3$ |
| **25. Jannat A et al.,** 2025 [50] | **-$PM_{2.5}$ concentration [ug/m$^3$]:** TVB: 4.75 ± 0.03; MLP: 4.65 ± 0.03<br>**-$NH_3$ concentration (ppm)** Average: 7.93 ± 0.34 ppm |
| **26. Li et al.,** 2024 [40] | **-$NH_3$ concentration (mg h$^{-1}$ cow $^{-1}$)** Average: 3113.4<br>**-$PM_{2.5}$ concentration (mg h$^{-1}$ cow $^{-1}$)** Average: 54.2 |

#### 3.2.2. Poultry Farms

Poultry facilities showed wide ranges of pollutant concentrations depending on housing type and management practices. $NH_3$ concentrations reached up to 175.7 ppm in high-rise houses [26], while Shepherd et al. (2015) reported daily $NH_3$ emissions ranging from 0.049 ± 0.004 to 0.136 ± 0.011 g/hen/day across different housing systems (conventional cage, aviary, enriched colony) [36]. Wang et al. (2020) observed seasonal variation, with $NH_3$ levels from 3.7 ± 1.6 to 5.0 ± 1.1 mg/m$^3$ [38].

$PM_{10}$ and $PM_{2.5}$ concentrations were particularly elevated in certain poultry housing settings. Ni et al. (2012) found $PM_{10}$ levels reaching over 4000 µg/m$^3$ in some barns [26]. Hayes et al. (2012) reported mean daily $PM_{10}$ emissions of 0.11 ± 0.04 g/bird and $PM_{2.5}$ emissions of 0.008 ± 0.006 g/bird [32]. In seasonal studies, $PM_{2.5}$ concentrations in poultry houses ranged from 1.07 ± 2.5 mg/m$^3$ (autumn) to 100 ± 21 mg/m$^3$ (summer) [38] (Table 3).

#### 3.2.3. Dairy Farms

Dairy facilities showed a wide range of $NH_3$ and PM emissions. $NH_3$ concentrations varied from 1.54 mg/m$^3$ in general barns to 2.13 mg/m$^3$ in lactating barns [28], with much higher emissions reported by Wu et al. (2020) [46]. In the Netherlands, Tulp et al. (2024) found $NH_3$ concentrations varying from 6.6 to 108.7 µg/m$^3$ depending on wind direction [29].

$PM_{2.5}$ concentrations reached up to 119 µg/m$^3$ inside dairy barns [49], exceeding corresponding outdoor levels (106 µg/m$^3$). Joo et al. (2015) found $PM_{2.5}$ mass concentrations of 67.8 ± 12.1 µg/m$^3$ and emission rates up to 2.8 ± 1.4 mg/min [27]. $PM_{10}$ concentrations were even higher, with values up to 577 ± 280 µg/m$^3$ indoors. Finally, Li et al. (2024) reported $PM_{2.5}$ and $NH_3$ emission rates of 54.2 mg/h/cow and 3113.4 mg/h/cow, respectively, in a cross-ventilated dairy barn (Table 3) [40].

### *3.3. Monitoring Methods and Data Quality*

The reviewed studies employed a wide range of monitoring strategies, instruments, and analytical approaches to assess ammonia ($NH_3$), $PM_{2.5}$, and $PM_{10}$ concentrations in livestock environments.

Monitoring locations varied significantly across studies and included measurements inside pig pens or poultry houses [25,32,33,37], between barns [44], at different heights within the facilities [26,45], and in outdoor areas near or surrounding the stables [28,29,36,48,49] (Table 4).

**Table 4.** Description of the data monitoring, analytical methods to monitor $NH_3$, $PM_{2.5}$, $PM_{10}$ level and data quality.

| Authors, Year [References] | Monitoring Sites and Time | Analytical Methods | | | |
|---|---|---|---|---|---|
| | | Instruments Analysis | Filters and Flow Rate | Models | Data Quality |
| **1. Choi et al.,** 2023 [25] | -Monitoring sites: NR<br>-Monitoring time: Piglet pens and growing finishing pig pens over a period of one and a half years in 2020 | $NH_3$ and PM:<br>portable gas detector (Gastiger 2000) and personal impactors connected to an Aircheck sampling pump. | $PM_{10}$ and $PM_{2.5}$: PTFE filter (37 mm, 2 um pore). Flow rate of 4 L per minute. | NR | NR |
| **2. Ji Qin Ni et al.**,2012 [26] | -Monitoring sites: In the top and bottom of the high-rise houses<br>-Monitoring time: NR | $NH_3$: one multi-gas photoacoustic Field Gas-Monitor | NR | NR | NR |
| **3. Jihoon Park et al.**, 2019 [39] | NR | $NH_3$: direct reading multigas monitor | NR | ANOVA | NR |
| **4. Qian-Feng Li et al.**, 2013 [41] | NR | $NH_3$: a real-time analyzer<br>$PM_{2.5}$: Partisol Model 2300 chemical speciation samplers. | HCD Nylon filter.<br>Flow rate: NR. | ISORROPIA-II | NR |
| **5. Dan Shen et al.**, 2019 [33] | -Monitoring sites: horizontal locations at different heights (0.5 m, 1.0 m and 1.5 m) in the middle of the barns.<br>-Monitoring time: from 07:00 to 19:00 at 2 h intervals for 6 d (7 times per day). From 1st to 12th April 2017. | $PM_{2.5}$: DustTrak™ II 8532 Handheld Aerosol Monitor | Prebaked quartz filters (47 mm diameter, Whatman Inc., Clifton, NJ, USA).<br>$PM_{2.5}$: Flow rate of 16.7 L/min for 12 h per day for 6 d | ANOVA | NR |
| **6. Y. Zhao et al.**, 2015 [37] | -Monitoring sites: NR<br>-Monitoring time: 3-year CSES project covered 2 single-cycle production flocks. | $NH_3$: fast response and precision photoacoustic multi-gas analyzer | Y-shaped sampling port with two dust filters and with two inline Teflon filters (47 mm filter membrane, 5 to 6 µm).<br>Flow rate: NR | GLIMMIX model | NR |
| **7. Yu Wang et al.**, 2020 [38] | -Monitoring sites: NR<br>-Monitoring time: August 2018, October 2018, and January 2019 | $NH_3$: $NH_3$-NO-$NO_2$ analyzer.<br>$PM_{10}$ and $PM_{2.5}$: four medium-volume air samplers | 6.26 mm-inside-diameter Teflon tubing.<br>$PM_{10}$ and $PM_{2.5}$ samples were collected at a flow rate of 100 L/min. | ANOVA using Duncan's LSD test | $NH_3$ measurement range: 0–100 ppm, sensitivity: 1 ppb |
| **8. Yaomin Jin et al.**, 2012. [42] | -Monitoring sites: 17 gas-sampling locations (GSLs) were selected at the site<br>-Monitoring time: NR. | Gas analyzer:<br>a photoacoustic infrared $CO_2$ analyzer, a fluorescence-based $H_2S$ analyzer and a photoacoustic multigas analyzer | To protect air using in-line membrane filters.<br>Flow rate: NR | AirDAC software | NR |
| **9. Li Q-F. et al.**, 2013 [43] | -Monitoring sites: Concentration of PM was monitored in the exhaust air and at an outside location.<br>-Monitoring time: NR | Inlet PM: beta attenuation PM monitor.<br>PM concentration in the exhaust air: TEOM model 1400a. | TEOM filters<br>Flow rate: NR | Strategy 1: Stream Method<br>Strategy 2: Single Stream and Dual Stream Methods | NR |
| **10. Casey et al.**, 2012 [44] | -Monitoring sites: between gestation barns 1 and 2.<br>-Monitoring time: NR | Gas analyzer: a photoacoustic IR multi-gas monitor INNOVA Model 1412 | NR | NR | NR |

**Table 4.** *Cont.*

| Authors, Year [References] | Monitoring Sites and Time | Analytical Methods | | | |
|---|---|---|---|---|---|
| | | Instruments Analysis | Filters and Flow Rate | Models | Data Quality |
| **11. Li Z et al.,** 2018 [45] | -Monitoring sites: various positions at 3 different heights<br>-Monitoring time: for 3 days from 07 to 19 at an interval of 2 h | $PM_{2.5}$—$PM_{10}$: DustTrakTMII8532<br>$NH_3$: JK40-IV portable gas detector | NR | ANOVA | NR |
| **12. Hayes et al.,** 2012 [32] | -Monitoring sites $NH_3$: measured continually in 4 locations in each house.<br>-Monitoring sites: PM 10 and 2.5: measured continuously inside the houses.<br>-Monitoring time: NR | $NH_3$: fast-response, high-precision infrared (IR) photoacoustic multi gas analyzer.<br>$PM_{10}$ and $PM_{2.5}$: TEOM equipped with the respective PM head | FEP Teflon tubing (0.95 cm) was used for air sampling to avoid $NH_3$ absorption: coarse filter and a fine dust filter (47 mm filter membrane, Savillex).<br>Flow rate: NR | NR | NR |
| **13. Von Jasmund et al.,** 2020 [30] | -Monitoring sites: $NH_3$ in the middle of the pen at a height of 1.47 m<br>-Monitoring Time: from March to July 2019 | $NH_3$ concentration: Polytron C300 equipped with a gas electrochemical sensor | NR | NR | Accuracy: 1.5 ppm ± 10% of the measured value |
| **14. Wu et al.,** 2020 [46] | -Monitoring sites: in the middle of the feedlot pen surface of the dairy farm<br>-Monitoring Time: daylight hours in May 2017 for 7 consecutive days | $NH_3$ concentration: UV/vis spectrophotometer | Filters: NR<br>Flow rate: 5 L/min | AEROMOD | NR |
| **15. Joo et al.,** 2015 [27] | -Monitoring sites: At the centre of each barn, 3 m below the roof of the barn.<br>-Monitoring time: July and August 2009, data were collected continuously during this period except for four days. | PM mass concentrations: 2 tapered element oscillating microbalances (TEOMs) and Beta ray attenuation particle monitor. | Filters: NR<br>Flow rate: 3.0 L/min | NR | NR |
| **16. Jin et al.,** 2010 [47] | -Monitoring sites: 17 points in all the stable<br>-Monitoring Time: NR | $NH_3$ emission: photoacoustic multi-gas analyser.<br>PM emission ($PM_{10}$-$PM_{2.5}$): TEOM tapered element oscillating microbalance. | Optical filter for each gas<br>Flow rate: NR | NR | Measurement accuracy of 2–3%; detection thresholds ppm for $NH_3$.<br>TEOM (pulsed fluorescence analyser): detection limit of 6.0 ppb and precision 1 ppb. |
| **17. Garcia et al.,** 2013 [48] | -Monitoring sites: 6 Different point in the stables<br>-Monitoring time: NR. | $PM_{2.5}$ concentration: GK2.05SH cyclone sampler | Teflon Millipore filters (37 mm) with a pore size of 0.45 mm (Fisher Scientific) to collect PM.<br>Flow rate: 3.5 L/min | NR | NR |
| **18. Dai et al.,** 2018 [35] | -Monitoring sites: not specified different points in houses<br>-Monitoring Time: NR | $NH_3$ concentration: air sampler (TH-110F).<br>PM concentration: Dustrak Drx Aerosol Monitor 8533. | Filters: NR<br>Flow rate: 0.8 L/min. | NR | NR |
| **19. Sheperd et al.,** 2014 [36] | -Monitoring sites: 9 in-house locations (3 locations per house) and one ambient location<br>-Monitoring Time: NR | $NH_3$ concentration: photoacoustic multi-gas analyzer. | Filters: Two dust filters in the air tubes, and with 2 inline Teflon filters<br>Flow rate: NR | NR | NR |

**Table 4.** *Cont.*

| Authors, Year [References] | Monitoring Sites and Time | Analytical Methods | | | |
|---|---|---|---|---|---|
| | | Instruments Analysis | Filters and Flow Rate | Models | Data Quality |
| **20. Tamar Tulp et al.,** 2024 [29] | -Monitoring sites: samples point 500 m around the stable. -Monitoring time: between 4 August 2021 and 13 October 2021 with an interval of two weeks | $NH_3$ concentration: a passive sampler: 'ALPHA', | A filter paper that was coated in citric acid, and a white PTFE (Teflon) membrane Flow rate: NR | 'MuMIn' and Akaike information criterion (AIC). | NR |
| **21. Schmith-ausen et al.,** 2018 [34] | -Monitoring sites: 2 points in Sections 1 and 2 of the houses -Monitoring time: from8 January to 25 June 2013 | $NH_3$: photoacoustic multi-gas analyzer | NR | NR | Accuracy 2–3% detection limits: 0.14 mg/m$^3$ |
| **22. Zenon Nieckarz et al.,** 2023 [49] | -Monitoring sites: 2 m above the floor, and the second one outside, 2 m above the ground -Monitoring time: NR | $PM_{2.5}$, $PM_{10}$ concentration: University Measure Systems with, laser sensor SEN0177 | NR | Gravimetric | The measurement error of the EDM107 analyzer is ±2 µg/m$^3$ and not exceeding ±9 µg/m$^3$ |
| **23. W. Zheng et al.,** 2020 [31] | Monitoring sites: Samples point in various directions in the house Monitoring time: from February to July 2016. | $NH_3$ concentration: 4 Intelligent Portable Monitoring Units (iPMUs) | Filters: Dust cup Flow rate: NR | NR | NR |
| **24. Zhifang Shi et al.,** 2019 [28] | Monitoring sites: 2 outside locations and 5 inside locations at 1.5 m above the floor Monitoring time: from July 4 to August 21, 2017 | $NH_3$ concentration: an integrated air sampler and a spectrophotometer | NR | NR | NR |
| **25. Jannat A et al.,** 2025 [50] | -Monitoring sites: TVB: in the center of the barn at 4 m from the ground. MKP: at the center of the rotary milking machine. -Monitoring time: continuously from 16 August to 22 December 2023 | IEQ Max (Denver, CO) multiple sensor platform system. $NH_3$: electrochemical sensor $PM_{2.5}$: mechanical sensor | NR | NR | $NH_3$ electrochemical sensor: Accuracy: ±20% Range: from 0.4 to 60 (ppm) $PM_{2.5}$: mechanical sensor Accuracy: ±20% Range: from 0 to 5000 ug/m$^3$ |
| **26. Li et al.,** 2024 [40] | -Monitoring sites: NR -Monitoring time: NR | Two self-developed environment-monitoring devices, the portable particulate monitoring unit (PPMU) and the portable gas monitoring unit (PGMU) $NH_3$: NE03-NH3 $PM_{2.5}$: PMSX003N | NR | $NH_3$: electro-chemical $PM_{2.5}$: Mie scattering | $NH_3$ manufacture: Range: 0–50 ppm Resolution: 0.1 ppm Response time:/ Accuracy: ±10 F.S. $PM_{2.5}$ manufacture: Range: 0–500 ug/m$^3$ Resolution: 1 ug/m$^3$ Response time: <1 ms Accuracy: ±10 ug/m$^3$ |

Legend: NR: not reported; PTFE: polytetrafluoroethylene; TEOM: tapered element oscillating microbalances; FEP: Fluoroethylenepropylene; OFIS: on farm information system, CAPECAB: Fibre Recovery Systems.

Monitoring durations ranged from short-term campaigns lasting several hours or days [27,33], to longer monitoring periods spanning weeks or months [29,50], and even multi-year studies [37]. Both continuous monitoring [28,50] and interval-based measurements conducted at regular time points [29,33] were considered (Table 4).

For $NH_3$ monitoring, photoacoustic multi-gas analyzers were among the most frequently used instruments, as reported by Ni et al. (2012), Casey et al. (2012), Hayes et al. (2012), Sheperd et al. (2014), and Schmithausen et al. (2018) [26,32,34,36,44]. These analyzers were particularly valued for their high sensitivity and real-time detection capabilities [34,47]. Other studies employed portable gas detectors, such as in Choi et al. (2023) and Li Z. et al. (2018) [25,45]; electrochemical sensors were used in Von Jasmund et al. (2020), Jannat et al. (2025), and Li et al. (2024) [30,40,50]; while UV/vis spectrophotometry was applied in Wu et al. (2020) [46]. Reported measurement accuracy ranged from ±10% to ±20% [40,50], with detection limits as low as 0.14 $mg/m^3$ in the case of electrochemical and photoacoustic sensors [30,34] (Table 4).

$PM_{2.5}$ and $PM_{10}$ were commonly measured using tapered element oscillating microbalances (TEOMs) [27,32,47], DustTrak monitors [33,35,45], gravimetric samplers [49], and beta attenuation monitors [27]. Filters included PTFE, Teflon, and quartz-based membranes [25,32,33,48], with flow rates ranging from 0.8 to 100 L/min [25,33,35,38]. Finally, most of authors did not report data filters (Table 4).

Several studies applied analytical or statistical models to evaluate spatial and temporal variability or atmospheric dispersion. ANOVA and its variants were used in at least five studies [33,38–40,45], while more advanced models such as GLIMMIX [37], AERMOD [46], ISORROPIA-II [41], and MuMIn with AIC [29] were also implemented (Table 4).

Only a minority of studies reported detailed data quality metrics. Some studies provided information on instrument accuracy (e.g., ±2–3% for $NH_3$ and ±2 to ±9 $\mu g/m^3$ for PM) [30,34,40,47,49], and a limited number described calibration software or validation protocols [42,49].

Overall, substantial heterogeneity in methodological choices was observed across studies, reflecting differences in farm characteristics, monitoring technologies, and research objectives. Notably, most studies did not report comprehensive data quality assessments (Table 4), and a considerable proportion failed to document lighting conditions, ventilation characteristics, or feed type, confirming notable gaps in methodological transparency.

### *3.4. Application of the VERA Protocol Parameters in the Included Studies*

Evaluation of included studies against the VERA protocol revealed heterogeneous adherence to its methodological standards.

#### 3.4.1. Housing System Description

Most of the included studies provided a basic description of the housing systems. Key details such as animal species and breed, building materials, insulation, and capacity were consistently reported across several studies [25,33,37,50]. However, some studies only partially addressed these parameters, with missing or incomplete information regarding internal layout or secondary technical features. Notably, Tamar Tulp et al. (2024) and Zhifang Shi et al. (2019) lacked adequate detail for at least one of the key descriptors required by the protocol (Table S1) [28,29].

#### 3.4.2. Measuring System

Information on the technical components and operating principles of the ammonia and particulate matter measurement systems was provided in nearly all studies. Most authors [26,33,38] described the type of instrument used, its functioning, and expected performance. Electrochemical sensors, photoacoustic analyzers, and gravimetric samplers were among the most commonly employed techniques. Nevertheless, some studies, particularly older or purely observational ones, did not adequately describe material characteristics or sensor calibration protocols [35,36] (Table S2).

3.4.3. Sampling Conditions

Overall, the assessment of sampling conditions indicated partial but meaningful adherence to the methodological standards outlined in the VERA protocol for both $NH_3$ and $PM_{2.5}$ and $PM_{10}$ measurements. In particular, for $NH_3$, most studies reported the use of cumulative or continuous sampling methods, with an adequate frequency of instrument calibration and control. However, key criteria such as on-site verification of measurements and validation according to international standards were frequently omitted. Similarly, for PM, although many studies reported compliance with general sampling procedures and provided complete datasets, comparable methodological gaps were observed (Table S3).

3.4.4. Emission Estimation Methods

The majority of studies adopted either mechanical or natural ventilation scenarios for emission estimates. Mechanical ventilation scenarios were most frequently reported [37,40], while a study also used ventilation rate and tracer gas methods such as $CO_2$ [29]. In higher-quality studies, combinations of estimation methods were employed [26]. Several studies, however, did not apply or did not report appropriate emission estimation strategies I accordance with VERA requirements [35,46] (Table S4).

3.4.5. Secondary Parameters Related to Gaseous Emissions

Ventilation rate was the most commonly reported secondary parameter, and was typically measured through all air outlets in mechanically ventilated buildings [33,38]. A small number of studies described alternative approaches suitable for naturally ventilated systems [34], although consistency and reporting quality varied. Not all studies calculated ventilation rates or reported other secondary indicators relevant to gaseous emission assessment [27,28] (Table S5).

3.4.6. Adherence to the VERA Protocol by AVI

The overall mean average Adherence VERA Index (AVI) of the 26 included studies was approximately 63%, with extreme values ranging from 25% to 100%. AVI scores were further stratified by animal species, grouping studies according to the livestock type investigated, as shown in Figure 2.

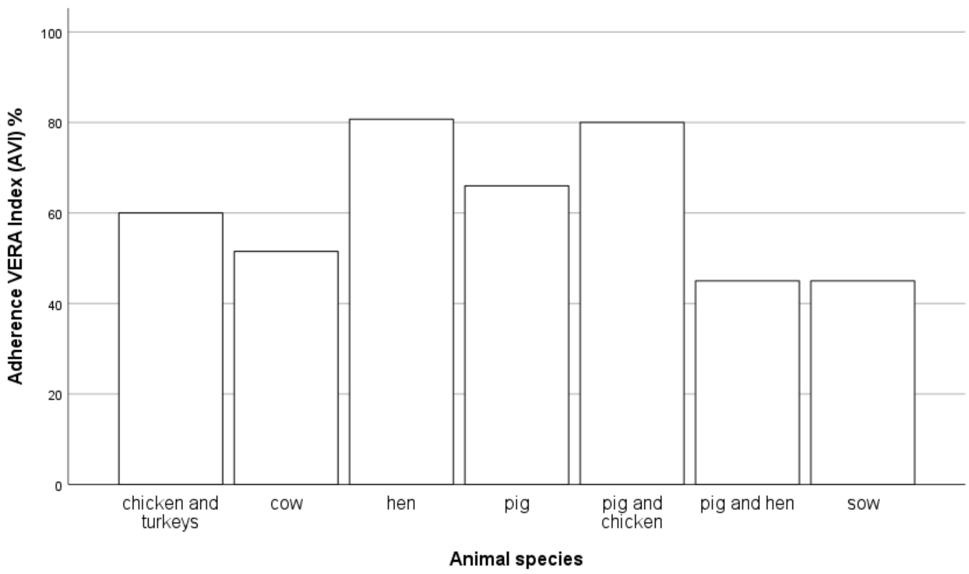


**Figure 2.** Distribution of AVI (%) by animal species.

Studies achieving the highest AVI scores consistently reported detailed descriptions of ventilation systems, instrument calibration procedures, and key environmental parameters.

In contrast, studies with the lowest AVI scores (<25%) were characterized by substantial deficiencies, particularly in the description of ventilation systems and emission estimation strategies.

The most frequent gaps included:

- Ventilation assessment (not measured or insufficiently described in a substantial proportion of studies)
- Sampling strategies (limited information on sampler placement and measurement frequency)
- Emission estimation methods (restricted use of tracer gases or directly measured airflow rate)

At the species level, studies focusing on cattle showed greater variability in AVI scores, ranging from highly detailed investigations to studies with severe methodological shortcomings. In contrast, studies on pigs and poultry showed similar but more consistently low mean AVI values.

Among studies with AVI scores below 25%, a higher frequency of $NH_3$ and PM concentrations exceeding occupational exposure limits was observed, suggesting a potential association between lower methodological quality and the underestimation of occupational risks. However, this association should be interpreted with caution. The observed association does not imply causality, as lower AVI scores may primarily reflect incomplete methodological reporting rather than intrinsically higher pollutant concentrations. Furthermore, unmeasured confounding factors (e.g., housing characteristics, ventilation efficacy, animal density, climatic conditions) may have influenced to the observed patterns.

## 4. Discussion

This methodological review highlighted a limited adherence to the VERA protocol, despite its value as a standardized framework capable of ensuring accurate, repeatable, and comparable emission measurements. Moreover, several of the $NH_3$ and $PM_{2.5}/PM_{10}$ concentrations reported in the included studies may pose health risks for workers. In particular, in some intensive poultry and swine farms, $NH_3$ concentrations exceeded occupational exposure limits, potentially representing a concrete occupational hazard when adequate ventilation systems or personal protective measures are not implemented [51]. These results underline the relevance of a One Health perspective, as inadequate monitoring practices affects not only workers' exposure but also animal welfare, and the environmental pollutants release. Addressing human, animal, and environmental health concurrently further supports the need for standardized monitoring frameworks.

Evidences from experimental and occupational studies reinforced these concerns. Davidson et al. [52] and Neghab et al. [53], demonstrated that $NH_3$ exposure can induce acute effects, including the release of cytokines and chemokines (e.g., IL-8, TNF-α), neutrophil recruitment, mucosal edema, and hyperemia with varying impacts across different regions of the respiratory tract (e.g., a ~5% reduction in FEV1/FVC). Chronic exposure was associated with structural airway damage, including bronchial mucosa thickening, goblet cell and mucous gland hyperplasia [52,54]. The underline pathogenetic mechanisms appear to involve oxidative stress with ROS production, activation of the NF-κB pathway with subsequent pro-inflammatory gene expression, and epithelial barrier dysfunction resulting from apoptosis or necrosis [55].

Although $PM_{2.5}$ and $PM_{10}$ concentrations were generally within Occupational Safety and Health Administration (OSHA) exposure limits, they frequently exceeded WHO guidelines for environmental exposure, thereby posing potential long term respiratory health risks, particularly in poorly ventilated environments or in the presence of organic

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dust [13]. Viegas et al. (2013) found an increased risk of respiratory conditions including asthma, chronic bronchitis, and hypersensitivity following exposure to elevated $PM_{2.5}$ and $PM_{10}$ levels [56]. The pathogenesis appears to be related to increased pro-inflammatory interleukins (IL-1$\alpha$, IL-1$\beta$, IL-6) in the nasal mucosa [57,58].

Consistent with these findings Donham et al. (1995) demonstrated adverse pulmonary effects at PM concentrations above 2.4–2.5 mg/m$^3$ for swine and 0.16 mg/m$^3$ for poultry, with workers showing a 5% decrease in post-shift FEV1 values [59].

Conversely, Vogel et al. (2012) investigating inflammatory responses to different PM size fractions collected from California dairy farms found that PM with a 4.2 μm cutoff induced greater pro-inflammatory cytokine release from macrophages, compared to smaller particles (2.1 μm cutoff) [60].

This review presents several strengths that enhance its scientific and methodological relevance. Firs, the geographical and typological coverage of the included studies was broad, encompassing investigations conducted in Asia, Europe, and North America, and involving swine, poultry, and dairy cattle production systems. Second, it's the specific focus on the VERA protocol represents a distinctive contribution: the systematic evaluation of adherence to this methodological standard provided an objective criterion for assessing procedural quality and identifying recurrent critical issues across studies. Furthermore, the evidence selection and assessment process was conducted using a structured and rigorous approach, in accordance with PRISMA guidelines, ensuring transparency, reproducibility, and robustness of the review's methodology. Beyond highlighting the need for wider adoption of the VERA protocol, the findings also suggest practical strategies to facilitate its implementation in both research and applied farm monitoring. First, the VERA-short checklist could be integrated into standard operating procedures (SOPs) adopted by laboratories and research groups as a minimum quality requirement prior data collection. Second, targeted training modules and technical guidelines could be developed for farm technicians, veterinarians, and environmental consultants, enabling the application of VERA criteria even in routine or low-budget monitoring activities. Third, the AVI could be integrated into certification schemes or voluntary environmental programmes promoted by producer organizations, thereby creating incentives for farms to adopt standardized monitoring practices. Finally, regulatory authorities or professional associations could use these findings to define baseline methodological requirements for $NH_3$ and PM monitoring, particularly with respect to ventilation measurement, sampling strategies, and instrument calibration, thus promoting gradual alignment with VERA principles within national or regional regulations.

However, several limitations should be acknowledged. A primary limitation is the marked methodological heterogeneity among the included studies, encompassing diverse instruments, measurement techniques, and monitoring protocols. In addition, key environmental variables such as temperature, humidity, or ventilation, were frequently reported incompletely, despite their substantial influence on emission dynamics. Data quality documentation was also often insufficient, with missing information on instrument calibration procedures or analytical precision, thereby limiting the assessment of result reliability. Moreover, incomplete reporting in several studies may have led to an underestimation of the actual methodological adherence, as missing elements were classified as non-compliant. The European origin of the VERA protocol represents another potential limitation, as its global application may introduce regional bias related to differences in farming systems, climate, and regulatory environments. Finaly, restricting inclusion to studies published in English, although justified by practical considerations, may have reduced the geographical representativeness of the evidence base by excluding relevant studies published in other linguistic.

## 5. Conclusions

This study introduces for the first time the Adherence VERA Index (AVI), a domain-based compliance mapping approach, and a minimum reporting set (VERA-short) that enables quantitative comparison of the methodological quality of studies assessing $NH_3$ and PM monitoring in livestock farms. Our findings demonstrate that recurring methodological gaps, particularly in ventilation assessment, sampling strategies, and emission estimation, coexist with frequent exceedances of exposure thresholds, especially in pig and poultry production systems, with potential direct implications for worker's respiratory health. We therefore propose the adoption of the VERA-short checklist (Table 4) as a minimum methodological standard for future research and guideline development. Grounded in a One Health perspective, this approach enhances international comparability, reduces uncertainty in exposure and risk assessments, and provides practical, implementable recommendations for researchers, industries, stakeholders and public health authorities. Finally, the expansion of surveillance programs and the strengthening of interdisciplinary collaboration, particularly in low- and middle-income countries, will be essential to ensure a more equitable and representative assessment of occupational exposure risks to airborne pollutants in livestock farming, as well as more robust evaluation of their environmental emissions.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments13010024/s1, Tables S1–S5: VERA protocol tables.

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**Data Availability Statement:** Data will be made available on request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| PM | Particulate Matter |
| PRISMA | Preferred Reporting Item for Systematic Review and Meta-analyses |
| AVI | Adherence VERA Index |
| TEOMS | Tapered element oscillating microbalances |

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